Tomasz Pfeifer, Lee Aucott, Aleksander Żak

Testing of solidification cracking susceptibility of MAG welded overlays on S355JR steel using a Transvarestraint test

Abstract: Application of the Transvarestraint test to assessment of solidification cracking susceptibility of overlay welds made by MAG method on S355JR steel has been presented. A specific test rig enabling to apply different strain of the test piece with high speed was designed. In the course of the research the weld pool temperature history was registered, cracking qualification was done and the examination of crack opening and HAZ using scanning electron microscopy and light microscopy was carried out. Solidification cracking temperature range of this material system was determined

Keywords: welding, cracking, MAG, Transvarestraint test

Introduction

Solidification hot cracking of welded joints is commonly regarded as one of the most hazardous of various types of cracking. For this reason the mechanisms of cracking and hot cracking resistance of different structural materials are a subject of thorough research. Such cracks, developing usually on grain boundaries, are generated in a weld at the end of a crystallisation process when a metal being the mixture of a liquid and a solid body is torn as a result of deformations related to weld material contraction accompanying crystallisation and self-cooling.

One of reliable tests enabling the assessment of steel susceptibility to solidification cracking is the Transvarestraint test. The methodology of this test has been developed directly on the basis of the Varestraint test whose precursors were Savage and Lundin [1]. However, neither of these tests have become standardised and, as a result, today there are many different versions of them [2].

The purpose of research conducted using the Transvarestraint test was to determine a temperature range in which solidification cracks are generated and develop. The range is determined on the basis of the measurement of the maximum crack length (MCL) generated in a sample subjected to a high-rate strain after welding as well as on the basis of a recorded temperature course in a weld [3-8]. Most publications related to the Transvarestraint test describe tests conducted using TIG welding without a filler metal. However, the publication [9] refers to the possibility of welding with a filler metal, which enabled determining the hot cracking resistance of a fill-

dr inż. Tomasz Pfeifer (Ph.D. Eng.) – Instytut Spawalnictwa, Zakład Technologii Spawalniczych /Welding Technologies Department/; M.Sc. Eng. Lee Aucott – University of Leicester; mgr inż. (M.Sc. Eng) Aleksander Żak – Frenzak ltd., Mikołów, Poland

er metal or of a specific material system (filler metal + base metal). In such cases the use of appropriate welding parameters, enabling the proper overlay weld fusion into the base metal is of great importance. This was the reason for undertaking tests aimed at the determination of hot cracking resistance and solidification cracking temperature range using the Transvarestraint for the following material system: electrode wire PN-EN ISO 14341-A-G3Si1 and steel S355JR (base metal).

The assessment of susceptibility to hot cracking and the determination of solidification cracking temperature range of such a material system is important from the Mint-Weld project implementation point of view (contract no. NMP3-SL-2009-229108). The tests involve the preparation of a reliable and useful numerical model of the development of interfaces during the welding and operation of welded joints. The model should take into consideration molecular dynamics phenomena in the atomic scale (the properties of interfaces, the chemical composition and structure), phase models in the nano/micro scale (the structure of grain boundaries and the chemical composition of interface boundaries), mesoscopic models tracking the front of interfaces (crystal growth and grain size distribution) as well as modelling using fluid dynamics in the macroscopic scale (heat and mass flow). The obtained results of the solidification cracking susceptibility assessment tests constituted necessary and very important input data for modelling the development of interphase boundaries in various scales.

The tests and their results presented below are a part of the MintWeld project implemented at Instytut Spawalnictwa within the confines of the 7th Framework Programme.

Course of tests and results

Transvarestraint test

The tests to determine the solidification cracking temperature range involved the use of a base metal in the form of 6 and 12mm-thick S355JR steel plates (300 mm × 200 mm) and an electrode wire PN-EN ISO 14341 – A – G3Si1 with a diameter of 1 mm. A 180mm-long overlay weld was made on the aforesaid plates, using a robotised standard arc MAG method. In all the tests the following constant welding parameter values were used: current 200 A, arc voltage 25 V and a welding rate of 15 cm/min. The Transvarestraint tests were carried out with a device built especially for this purpose in the Frenzak Sp. z o.o. company in Mikołów, one of the MintWeld project

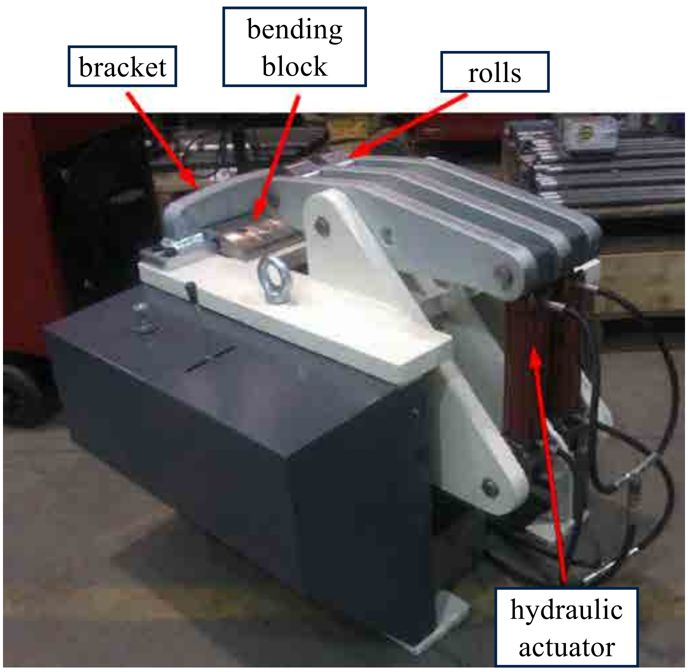

Fig. 1. Device for Transvarestraint test and manner of mounting and deforming test piece

partners. The testing device is presented in Figure 1. The test plates were mounted in a repeatable manner under a fixing bracket on exchangeable blocks with a provided arch of appropriate radius (Fig. 1). Next, using the MAG method and adopted parameters a 180mm-long overlay weld was made. During welding the temperature of a weld pool was measured by a D-type thermocouple (tungsten-rhenium; dia. 0.25mm) directly in the liquid pool. After welding (welding arc termination generated a signal for a bending device) the plate was deformed by means of a hydraulic actuator and bent on a steel block perpendicularly in relation to the direction of welding; the rate of bending being 24 mm/s. Bend radiuses, made on a one edge of the steel block were selected in a manner making it possible to generate (on the surface) a strain corresponding to a specific elongation percentage, i.e. 0.5%, 1%, 2%, 5%, 10% and 20%. For this reason, for each S355JR steel plate 6 tests were carried out each time changing a steel block for another one, with a different bend radius.

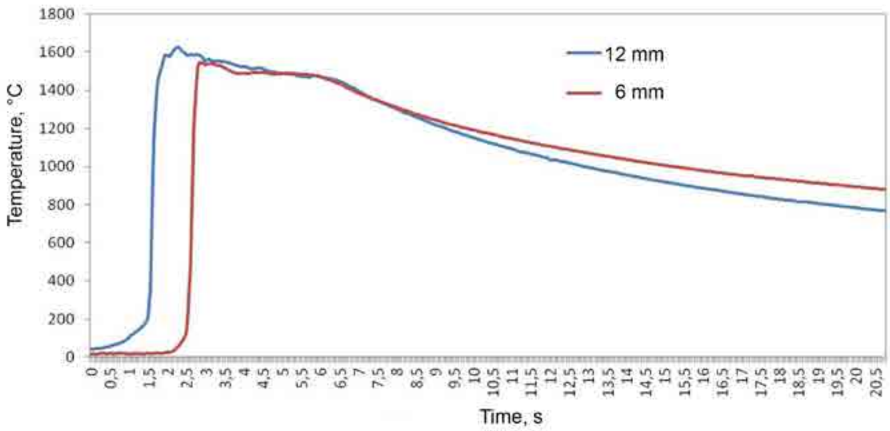

Fig. 2. Results of temperature measurements in liquid metal pool during surfacing in Transvarestraint test

Temperature measurements

Temperature measurements carried out during welding revealed that the welds solidified at approximately 1460°C (Fig. 2) in the case of both tested plate thicknesses. In the case of the 12mm-thick plate the maximum registered temperature of the liquid metal was approximately 1622°C, which significantly exceeds a liquidus temperature. Figure 2, presenting the results of a temperature measurement in the weld pool, shows a relatively low temperature gradient from the maximum temperature to the solidification temperature. Such a gradient results from the heat release related to the phase transformation of the solidification process. The temperature measurements revealed that for the 12mm-thick plate the cooling rate in the above range was approximately 40°C/s, whereas for the 6mm-thick plate it amounted to approximately 19°C/s.

Solidification cracks appear in the last crystallisation phase, at a temperature below which the whole material is fully solidified. The 6mm-thick plates revealed a significantly greater number of solidification cracks (Table 1) than in the 12-mm thick plates. The reason behind such a difference is the fact for the same welding parameters the heat emission from the 6mm-thick plate is much slower. As a result, the weld remains significantly longer in the area above the solidification temperature; on the basis of Figure 2 it is possible to determine the cooling rate at the liquidus–solidus temperature range. In the aforesaid range the material is a mixture of liquid and solid phases, and therefore is significantly less susceptible to solidification cracking. After solidification, a cooling rate is approximately 74°C/s for the 12mm-thick plate and 51°C/s for the 6mm-thick plate.

Quantitative analysis of cracks

After the bend test conducted transversely in relation to the direction of surfacing, the analysis of cracks generated in the crater was carried out. Table 1 presents the results obtained and Figure 3 shows the example of

Table 1. Results of analysis of solidification cracks in the craters of overlay welds made during the Transvarestraint tests

Strain %	Plate thickness, mm					
	6			12		
	Number of cracks	MCL, mm	TCL, mm	Number of cracks	MCL, mm	TCL, mm
0	0	0	0	0	0	0
0,5	0	0	0	0	0	0
1	1	10	10	0	0	0
2	2	11	14,5	1	8	8
5	5	21	36	1	3	3
10	16	20	36,5	3	8	19
20	34	21	40,5	4	9	26

Note:
MCL – Maximum Crack Length
TCL – Total Crack Length

Fig. 3. Solidification crack in the crater of weld made on 12mm-thick plate with 20% strain, used in Transvarestraint test

the crater in the overlay weld made on the 12mm-thick plate with a 20% strain in which solidification cracks were observed.

Visual tests and crack length measurements revealed that an increase in the strain degree is accompanied by an increase in the number of cracks as well as an increase in the maximum length of the solidification crack. Figure 3 presents a longitudinal crack in the weld axis formed at a significant strain. The crack was generated at the interface of grains, developing from the overlay weld edge towards the main axis of the weld and is a typical example of a solidification crack.

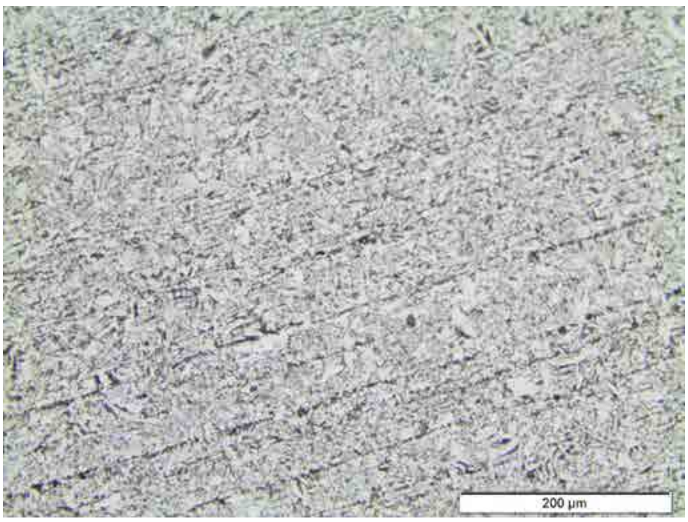

Fig. 4. Structure of S355JR steel base metal, visible banded structure of ferrite and pearlite

The latter part of this publication presents the results of the metallographic tests of this crack and the areas adjacent to it.

Metallographic tests

Metallographic tests were carried out for the test pieces cut out of the 12mm-thick plates, which during surfacing were subjected to the greatest strain (20%). The tests included observations with a light microscope and the structural analysis of the base metal, heat affected zone and, in particular, the overlay weld line of fusion into the base metal. The tests also involved the observation of the crack surface using a scanning microscope. Figure 4 presents the structure of the base metal which was not exposed to any welding-related heat impact, and thus was free from any structural changes.

Figure 5a presents the structure of the material approximately 1 mm away from the fusion line, in the HAZ area adjacent directly to the base metal. This area revealed only small changes in the microstructure (small amounts of bainite). Figure 5b presents the HAZ area near the fusion line. During surfacing, the area reached a temperature close to the melting point. The

HAZ has a coarse-grained structure composed mainly of ferrite and bainite.

Figure 6 presents the microstructure in the fusion line area both on the base metal side and on the overlay weld side. During the Transvarestraint test the area was completely molten. Welding materials of a similar chemical composition is accompanied by the epitaxial grain growth. In this process a liquid crystallises forming new grains directly from the solid phase from the base metal located underneath. The grains are anisotropic as they grow in accordance with a heat flow direction. In this manner a characteristic columnar structure is obtained.

Figure 6a presents a typical columnar structure, in which it is possible to observe the Widmanstätten structure formed directly on the ferrite of grain boundaries. Figure 6b shows a structure composed mainly of acicular ferrite and polygonal ferrite. Impurities present in the steel or weld metal such as phosphorus and sulphur are usually situated between dendrites formed during crystallisation. For this reason, impurities usually concentrate in the weld axis at the end of the crystallisation process, which significantly increase the likelihood of solidification cracking occurence.

At the next stage of the tests the surface of a crack in the overlay weld was examined. The crack was sampled for a test piece which underwent ultrasonic cleaning and was observed by means of a scanning electron microscope FEI Sirion 200. Figure 7 presents the dendritic structure of the crack surface. The structure indicates that the crack is a real solidification-type hot crack.

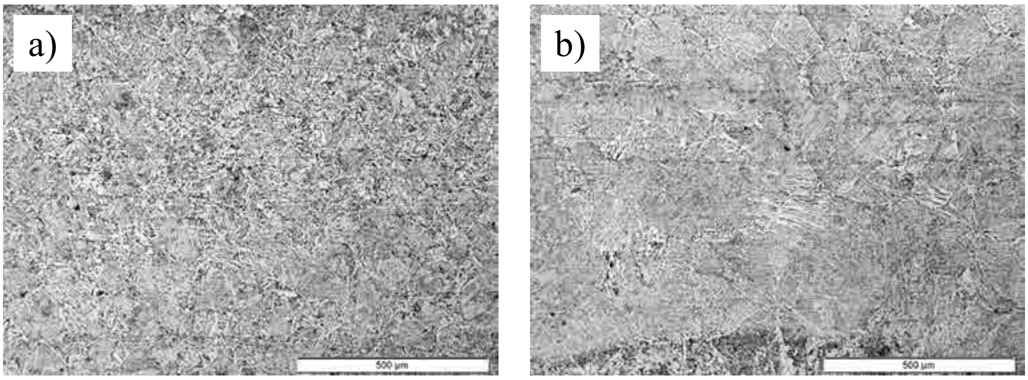

Fig. 5. a) Structure of material in S355JR steel HAZ, in area adjacent to base metal, coarse-grained structure, b) Coarse-grained structure in HAZ adjacent to fusion line, visible bainite and small amounts of ferrite

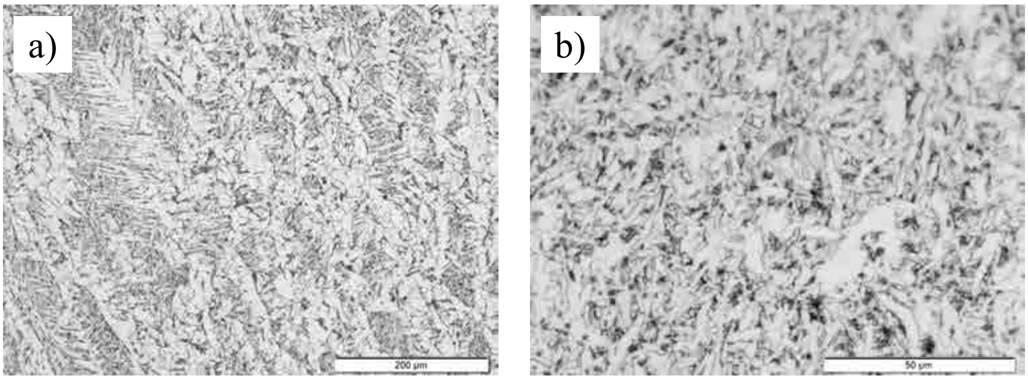

Fig. 6. Microstrucure in fusion line area, a) view from base metal side: visible acicular ferrite and Widmanstätten structure, b) view from overlay weld side: acicular ferrite and polygonal structure

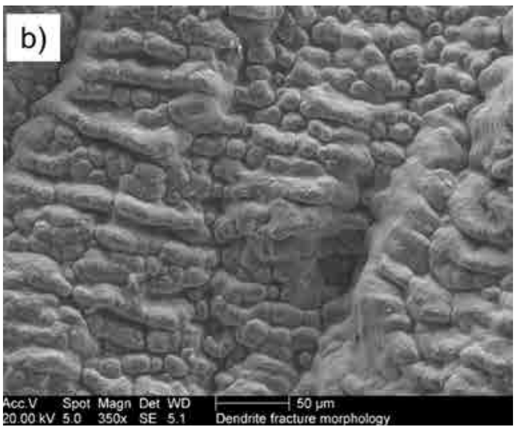

Fig. 7. Results of tests of solidification crack surface; a) sample preparation manner; b) image of tested surface obtained from scanning electron microscope

Determination of solidification cracking temperature range

In order to determine the temperature range of solidification cracking in the overlay welds made on the 12mm-thick plates, the longest crack recorded in all tests with a various strain degree was divided by the welding rate used in a given test. This was done in order to determine a time interval (crack length 9 mm, welding rate 2.5 mm/s, crack formation time interval 3.6 s). Afterwards, the time interval was plotted on a diagram presenting weld pool temperature values recorded during surfacing. The diagram enabled the determination of the temperature range (above a solidification temperature) in which a crack may develop when the weld material remains a mixture of liquid and solid phases. The wider this range, the higher the material susceptibility to solidification cracking. Figure 8 presents the methodology of determining a solidification cracking temperature range.

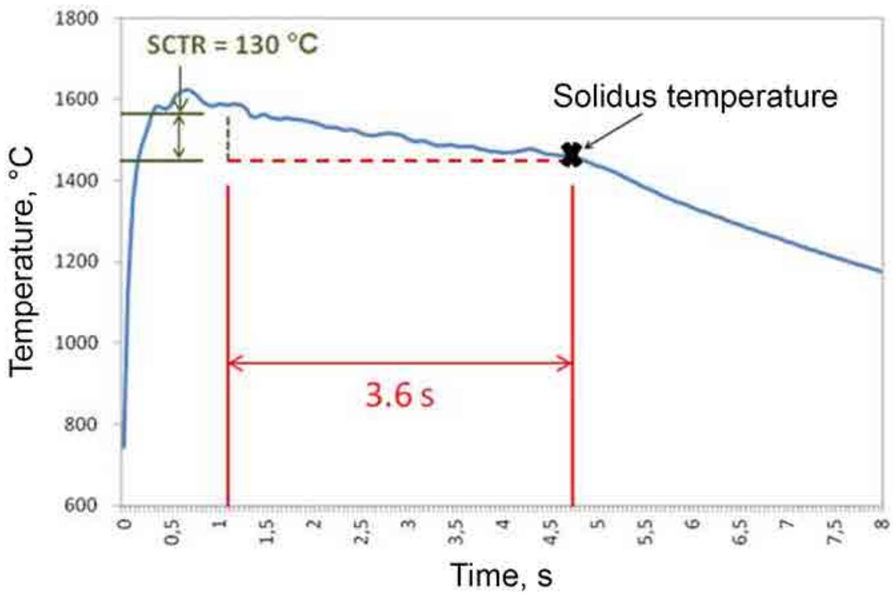

Fig. 8. Temperature of liquid metal pool and methodology of determining Solidification Cracking Temperature Range (SCTR) for overlay welds made of 12mm-thick S355JR steel plates

The tests revealed that the Transvarestraint test can be used to determine the Solidification Cracking Temperature Range for MAG-welded overlay welds made with a wire G3Si1 on S355JR steel, subjected to a strain equal up to 20% elongation. The determined temperature range amounts to 130°C. The obtained value is significantly higher than values presented in reference publications (< 50°C). However, most of the described tests aimed to determine the hot cracking resistance of a base metal. For this reason the tests were conducted using the TIG method without a filler metal. Instead, the base metal underwent remelting. The higher SCTR values obtained in the tests refer to a specific material system (base metal + filler metal) and may result from greater stress concentration.

Concluding remarks

The applied testing methodology and the test rig used in the research made it possible to carry out a modified Transvarestraint test with a various strain degree and determine a Solidification Cracking Temperature Range during surfacing 6mm-thick and 12mm-thick S355JR steel plates. The modification of the Transvarestraint test consisted in MAG surfacing instead of remelting a base metal by means of the TIG method. The modified test proved useful for the assumed test objective, i.e. to develop input data for welding process modelling in respect of developing interfaces. The tests also enabled the development of a methodology for liquid metal temperature measurements during MAG surfacing as well as made it possible to record temperature changes during the liquid metal pool solidification and weld cooling.

The tests revealed that heat flow impeding conditions cause an overlay weld to remain a mixture of liquid and solid phases far longer than a material subjected to remelting only, which favours hot cracking. The Transvarestraint test carried out for the 6mm-thick test pieces revealed a significantly greater number of cracks than that involving the use of the 12mm-thick test piece, applying the same surfacing parameters and bending conditions.

The determined value of the Solidification Cracking Temperature Range (SCTR) for the MAG-surfaced 12mm-thick plate is significantly higher than the value determined in the Transvarestraint test conducted with the TIG method and without the addition of a filler metal. The use of the MAG method and making an overlay weld during a Transvarestraint tests increases the probability of hot cracking due to the greater concentration of stresses.

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